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Structural Monitoring of a Weapons Test Unit Using Imaging Methods for Dynamic Signature Analysis

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ABSTRACT

A methodology to identify structural changes in weapons systems during environmental tests is being developed at Lawrence Livermore National Laboratory. The method is coherence based and relies on comparing the "dynamic signature" response of the test article before and after an environmental test or test series. Physical changes in the test article result in changes in the dynamic signature and are mapped to an image matrix where a color scale represents changes in sensor-to-sensor coherence. This methodology is convenient because it allows an image to represent large amounts of information in a very compact form, where even subtle system changes may be easily and quickly identified. Furthermore, comparison of the dynamic signature response data before and after any test event can be made on a quasi-real-time basis. This approach is particularly useful on large and/or complex test articles where many sensors are present, and large volumes of data are generated.

Background

One of the main goals of environmental testing is to assess any structural changes to the test article throughout the course of the testing process. One of the challenges associated with large and/or complex test articles is that they require large numbers of sensors in order to monitor the structural changes. Large numbers of sensors lead to large volumes of data to be analyzed, which can be a time consuming process. Ideally, examination of collected test data would be made in "real time" so that forethought could be put into subsequent tests. Significant changes to a mechanical system after any one test might merit further investigation of the test article.

In 2002, a series of environmental tests was performed at Lawrence Livermore National Laboratory on a weapons test unit over a five-month period. The goal behind the testing was to assess structural changes to the warhead after a simulated lifetime of environments. The test unit was equipped with 77 channels of acceleration, 8 channels of strain, and 17 channels of temperature. The environmental tests consisted of vibration and shock inputs combined with temperatures ranging from –54°C to 74°C. Before and after each prescribed environmental test, a short "dynamic signature" (DS) test was run. The goal of each DS test was to capture the unique dynamic signature of the test unit in response to a fixed flat-band input of random vibrations. The signatures were used to represent the current mechanical state of the test unit. A comparison of mechanical states before and after each prescribed environmental test would help to identify potential structural changes.

Because of the large number of sensors on the weapons test unit, comparisons between state changes for all combinations of sensor pairs became challenging from an analytical standpoint. To solve this problem a coherence-based methodology was developed to map the state changes into an image matrix by way of color visualization. The image stores large amounts of information in a very compact form, and significant state changes are easily identified in respective images through changes in image intensity.

Previous Work

Hammond and Waters [1] presented an overview of modal analysis, which was successfully applied to systems for studying vibration modes. Auweraer and Hermans [2] used coherence analysis in autoregressive vector modeling. Ning and Wei [3] applied multichannel coherence analysis to study helicopter vibrations. Work described in this paper addresses a much larger dataset in terms of sensors, tests and modes.

Dynamic Signature Analysis

A structure's DS can be influenced by many factors including: boundary conditions (i.e., fixturing/mounting configurations), the steady or gradient thermal state of the structure, its orientation, or the magnitude of input spectrum. However, if all these influences are held constant, then comparisons in dynamic signature before and after a given environmental test can potentially reveal structural changes. One traditional and simple approach to determining changes in a system would be to compare frequency response functions for selected channel pairs. This can be quite effective for tests with small numbers of channels; however, as previously mentioned, it can become computationally expensive and time consuming for systems with large channel counts. The approach taken to assess structural changes to the weapons test unit compared the coherence between every pair of sensor signals, $x(n)$ and $y(n)$, before and after a test event. This was accomplished by computing estimates for the auto and cross correlation functions:

$$\hat{R}_{xy}(m) = \begin{cases} \displaystyle\sum_{n=0}^{N-|m|-1} x(n)y^*(n+m) & m \geq 0 \\ \hat{R}^*_{xy}(-m) & m < 0 \end{cases} \qquad \text{Repeat for } \hat{R}_{xx}(m) \text{ and } \hat{R}_{yy}(m) \tag{1}$$

From these estimates the power spectra were calculated:

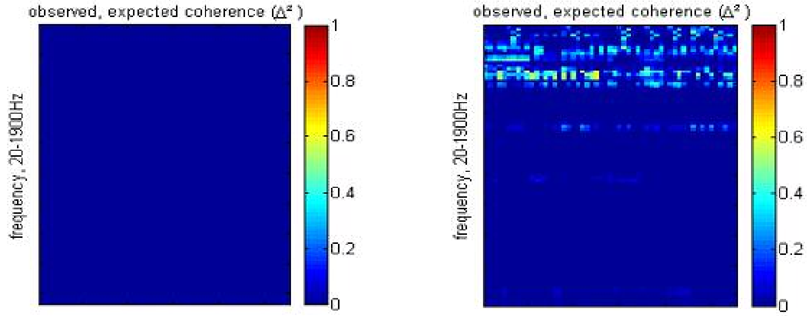
$$S_{xx}(\omega) = \sum_{m=-\infty}^{\infty} R_{xx}(m)e^{-j\omega m}, \; S_{yy}(\omega) = \sum_{m=-\infty}^{\infty} R_{yy}(m)e^{-j\omega m}, \; S_{xy}(\omega) = \sum_{m=-\infty}^{\infty} R_{xy}(m)e^{-j\omega m} \tag{2}$$

Finally, the coherence between $x(n)$ and $y(n)$ is calculated by:

$$C_{xy}(\omega) = \frac{|S_{xy}(\omega)|^2}{S_{xx}(\omega)S_{yy}(\omega)} \tag{3}$$

The coherence function was chosen because the measure of the output of a structure to the input at every frequency ω is scaled from 0 (incoherent) to 1 (coherent). This is very convenient from a metrics standpoint. A disadvantage of this metric is that it provides no immediate physical insight as to the cause of coherence changes. However, the methodology, as outlined in this paper, focuses more on assessing qualitative changes to a structure as opposed to quantitative differences. The images produced allow for quick qualitative assessment and limited quantitative information such as which sensor locations are measuring change. Further investigation or testing can then be performed to root out the cause of the change.

As stated earlier, a DS test was run before and after each environmental test event. Coherence functions were then calculated for all possible combinations of channel pairs for each DS test run. The differences in coherence between the run before and after were then mapped to a color gradient scale in the following manner: no change in coherence (i.e., difference of 0) was assigned blue; a large change in color (i.e., difference of 1) was assigned red. This was then plotted in a color image with frequency along one axis and all permutations of channel pairs on the other axis. An example is shown below in Figure 1. A process schematic for how the comparisons were performed is shown in Figure 2. The calculations were performed using MATLAB [4] running on either a PC or UNIX machine.



0 – no change (blue)

1 – large change (red)

(a) (b)

Figure 1: Image matrix showing: (a) no structural changes, (b) indications of state changes.

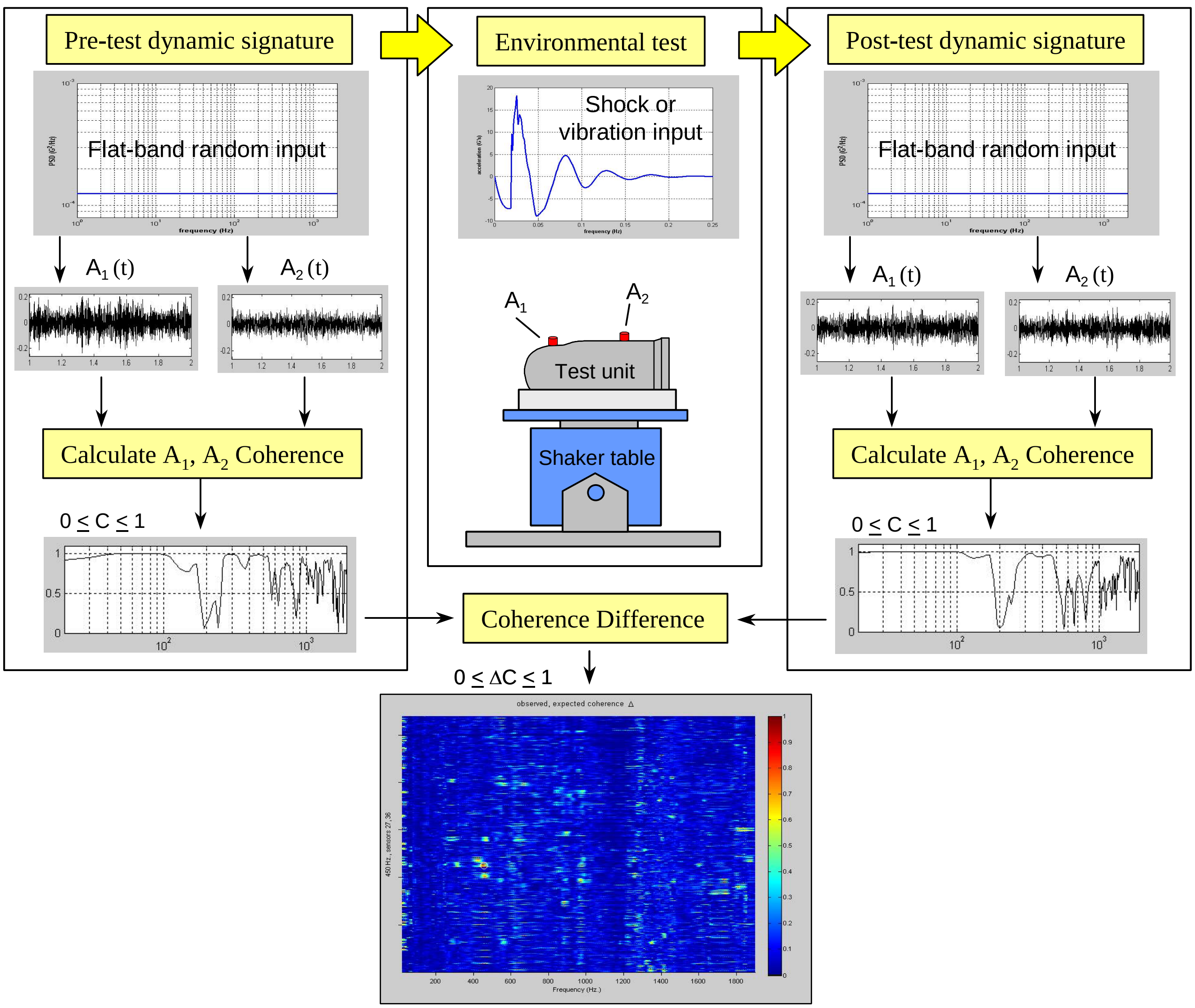


Figure 2: Process schematic for dynamic signature analysis
(example case showing comparison between sensors A_1 and A_2).

Proof of Concept Studies

Several experiments were performed as part of the developmental process to qualify the methodology for use. One such experiment was aimed at determining how sensitive the approach would be for very small changes to a system. The experiment was conducted on a fixture used to hold parts for environmental testing. Parts used in this fixture would normally be secured in place by a clamp ring with eight perimeter bolts, however for the purposes of this particular experiment only the clamp ring was tested, without included parts. A total of 11 different sensors were placed on or around the clamp ring at various locations (see Figure 3). The objective of the experiment was to record six different states on the fixture clamp ring and then compare the results using the mapped color image. Before and after each state, a DS run was performed using a broadband random input of 1 G_{rms}. The first state was set to the baseline configuration of the fixture in place on the shaker table. No changes were made in the second state so that repeatability could be checked. For the third state, one of the clamp-ring bolts was loosened from a predetermined torque to just “finger tight.” For the fourth state, the loosened bolt was retightened back to the original torque specification. In the fifth state, a washer with a thickness of 0.075 inches was added underneath the clamp ring at one bolt location, causing the clamp ring to not sit flush-up against the fixture at that location. For the sixth state, the washer was removed, and the setup was returned to its original baseline configuration. The steps are shown in Figure 4; the results are presented in Figure 5.

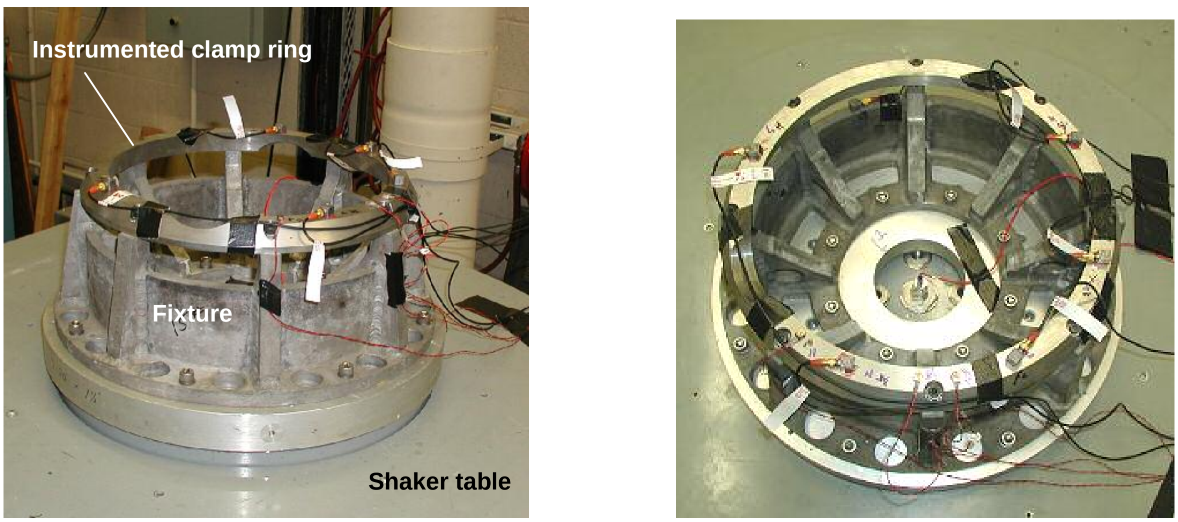


Figure 3: Pictures of vibration fixture with instrumented clamp ring.

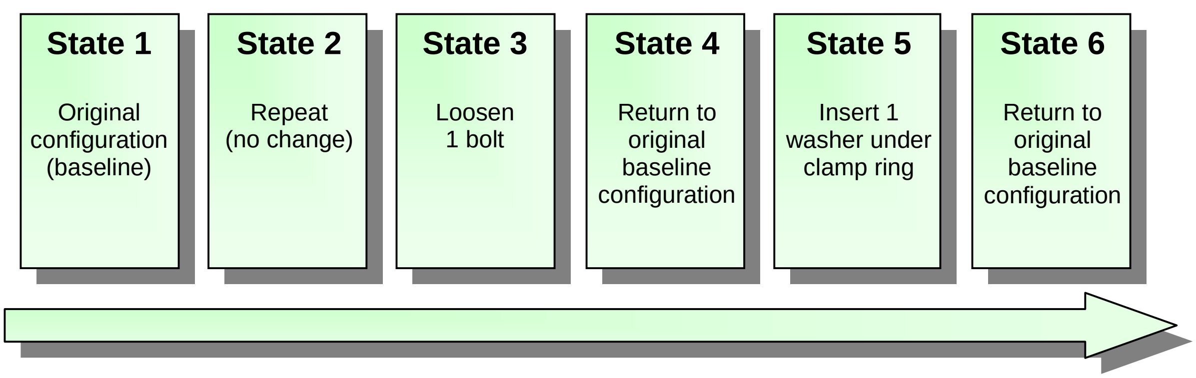


Figure 4: Step process for proof of concept test using part fixture.

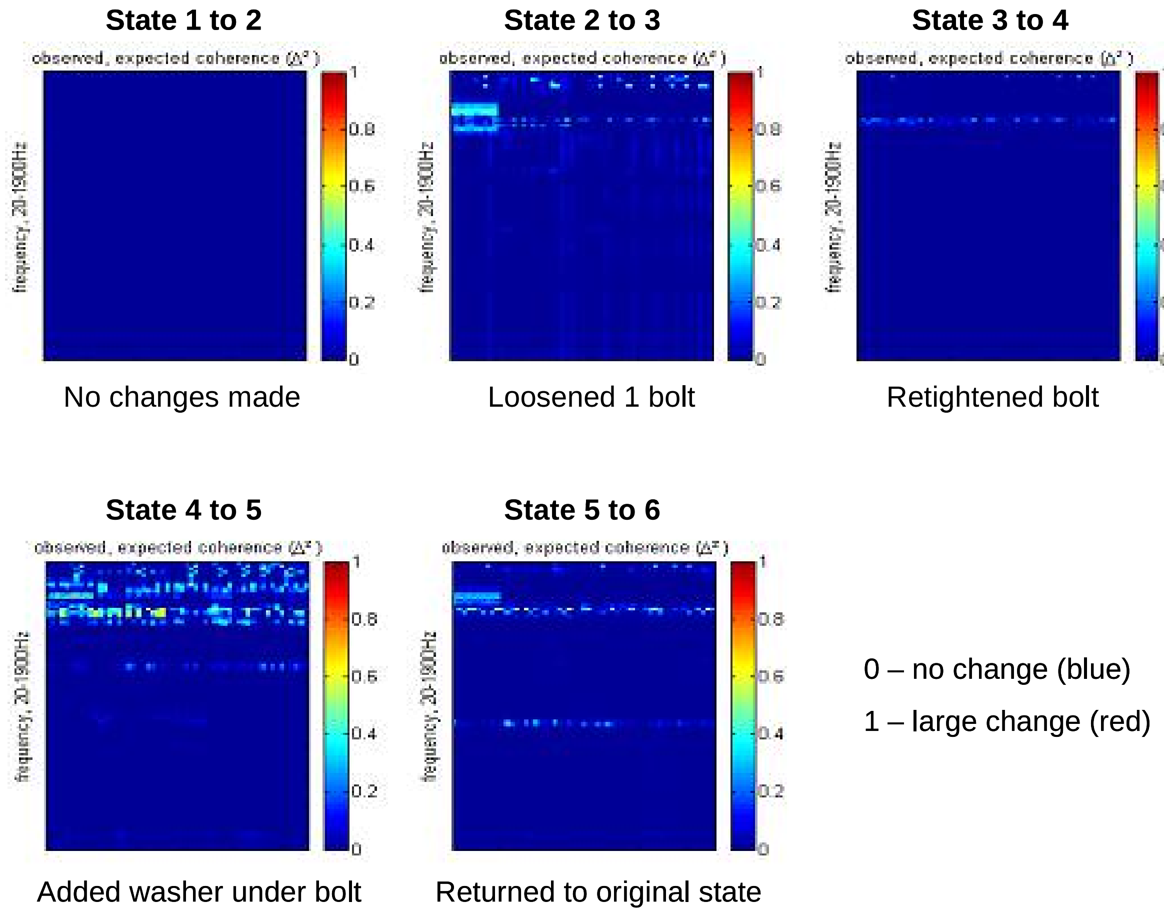
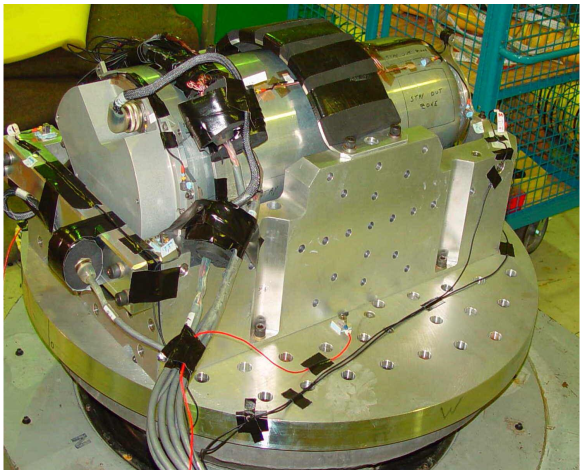


Figure 5: Comparison of results for proof of concept experiment.

The images from Figure 5 show expected changes that occurred to the system in States 3 and 5. In fact, the image depicting State 6, where the experiment was returned to the baseline condition shows some residual change to the system from State 1. After viewing this residual change from baseline data, the clamp ring was more closely inspected, and it was determined that it had been slightly plastically deformed in the region where the washer was introduced under the clamp ring. Upon completing this small experiment, it was determined that the methodology was sensitive enough to capture even subtle changes such as the loosening of a bolt.

Use of Dynamic Signature Analysis on Weapons Test Unit

In 2002, a full-scale engineering test series was conducted at Lawrence Livermore National Laboratory on a weapons test unit with the goal of assessing structural changes to a warhead after a simulated lifetime of environments. Overall, a total of 126 environmental tests were performed on the test unit. The tests consisted of vibration and shock inputs of various time durations conducted at cold, ambient, and hot temperatures. The test unit was heavily instrumented with 77 accelerometers, 8 strain gages, and 18 thermal sensors (RTDs). A picture of the setup is shown in Figure 6.



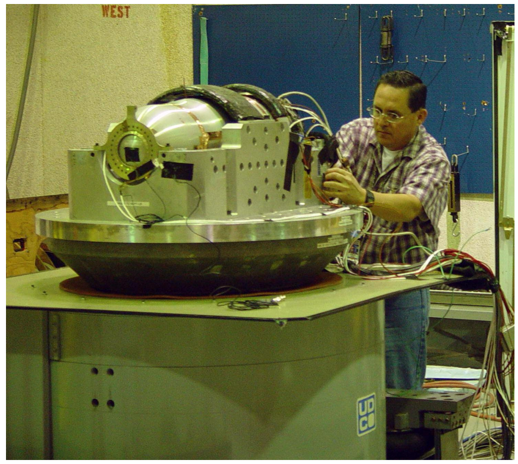
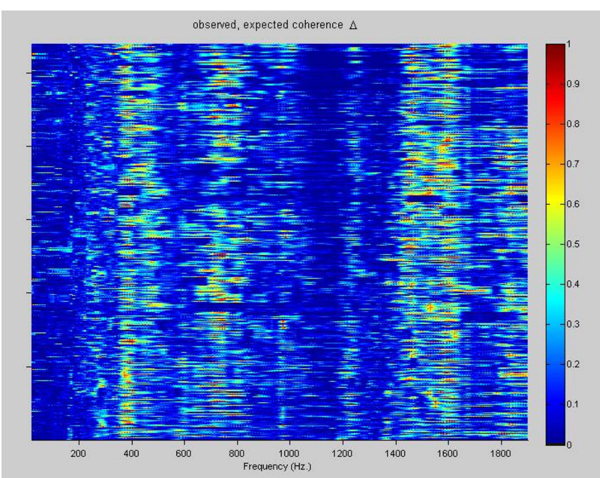


Figure 6: Pictures of instrumented weapons test unit.

In between each environmental test, a DS test was performed. Because the tests were performed sequentially, the post-DS test for Test 2, for example, could also be used as the pre-DS test for Test 3. By testing in this manner the overall number of DS tests were reduced. DS tests were also performed before and after any major temperature ramp, or anytime a fixture change was made. In general, anytime a boundary condition changed in the setup, or a different sensor was used, a DS test was performed. At the end of testing, approximately 150 DS tests had been performed. The DS test itself utilized a flat-band random input of 0.5 G's rms over a frequency band of 10–2000 Hz. Each DS test lasted 30 seconds, during which time the data was simultaneously captured on all channels. Once the data was collected, it was stored in data matrices. Comparison between any two data matrices was made possible with a software signal-processing algorithm that was developed at Lawrence Livermore. The software program performed the coherence calculations and produced the color image matrix, which represents the difference in coherence between data matrices for all sensor pair combinations.

The use of DS analysis played an important role in helping to assess structural changes throughout the duration of the testing. For the sake of this paper, two examples will be given. One such example involves only a change in temperature to the test unit. Thermal conditioning of the test unit throughout the testing process was accomplished by placing a foam igloo, having 4-inch walls, over both the test unit and shaker head. Conditioned air was then pumped into the igloo until a steady state condition was reached throughout the test unit. Figure 7 shows an example where the only change to the system was from heating the unit from a steady state ambient condition (+22°C) to steady state hot extreme of +71°C.



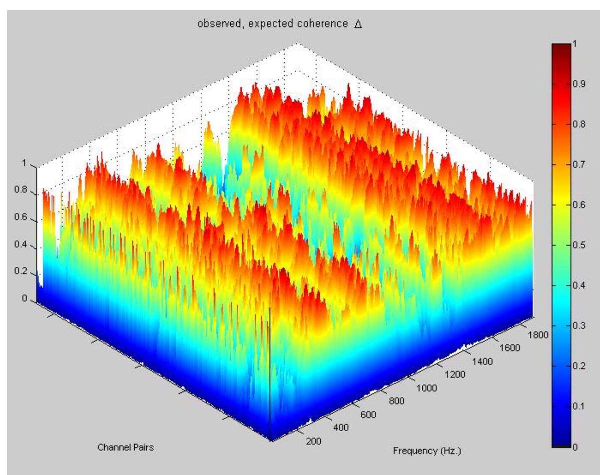


Figure 7: Results from DS comparison for temperature change only (shown as a 2D and a 3D image).

Another example of a structural change was identified by a shock test performed at a cold temperature. Changes noted in the DS comparison image after the shock test prompted further investigation. Radiographs were taken of the test unit following the incident, which revealed an internally damaged component. The DS image from this incident is shown below in Figure 8.

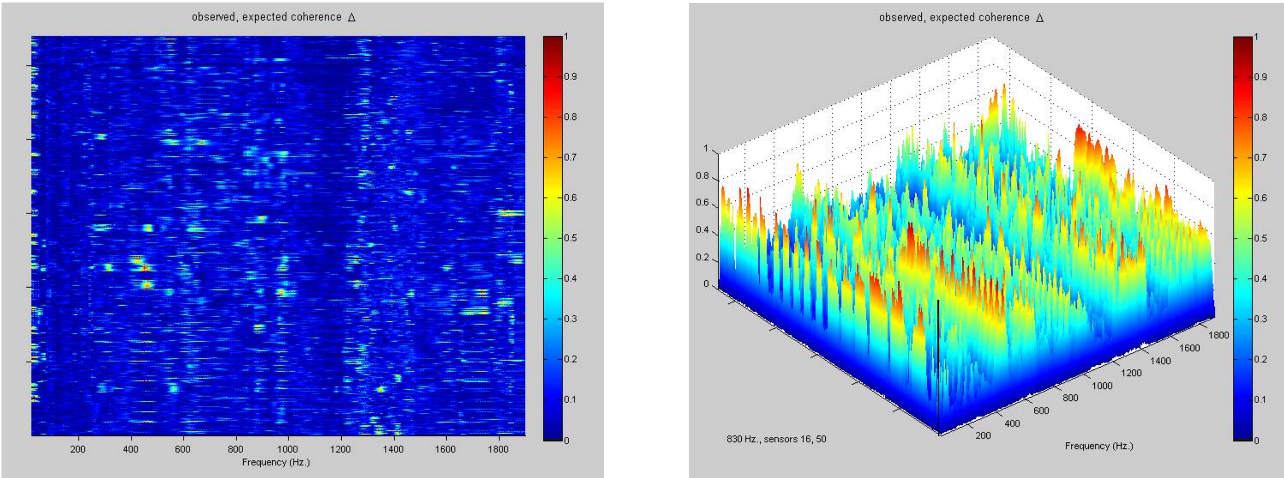


Figure 8: Results from DS comparison revealing cracked component (shown as a 2D and a 3D image).

Overall, this methodology proved to be quite useful in determining the health and integrity of the test unit throughout the testing process. Some of the benefits were that comparisons of the DS tests could be done quickly on a quasi-real time basis in spite of the large channel count. Typically, once the data matrices had been collected, DS comparison images could be generated in less than 10 minutes and provided a good qualitative indication of whether a structural change occurred. Another benefit was that the images were capable of flagging sensor malfunction because changes would appear across large frequency bands for particular sensor pairs.

Conclusions

This paper presents a methodology for assessing structural changes to an instrumented structure. The method is coherence based and relies on comparing the DS response of the test article before and after an environmental test or test series. Structural changes are mapped to an image matrix where a color intensity scale represents changes in sensor-to-sensor coherence. The benefit to using this methodology is that it presents large amounts of structural information in a compact form. This is particularly useful on large and complex test articles where many sensors are present and large volumes of data are generated. The methodology has proven to be sensitive enough to capture even subtle changes and can be done on a quasi-real-time basis.

The method can be further improved. In its current state, the methodology is well suited to provide qualitative results. Additional quantitative information would benefit as well. For example, quantitative measurements of increase or decrease in stiffness or damping is not provided. Furthermore, changes between perfectly correlated or perfectly uncorrelated measurements do not appear in the image matrix because both yield a state-to-state difference of zero. Currently, there are plans to develop an FRF-based algorithm to address these issues.

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